



Experimental Exergetic and Energetic Analysis of Different (PV) Array Configurations

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HIGHLIGHTS

- The average exergy efficiency of the case 2p*2p compared with case 2s*2s was 55.9%.
- The average exergy efficiency of the case 2p*2p compared with case 4p was 63.69%.
- The average exergy efficiency of the case 2p*2p compared with case 3p*1s was 78.9%.

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ABSTRACT

It is well known that photovoltaic (PV) can be connected in parallel, series, and parallel series. In this study, four PV panels are connected in four different ways, i.e., 4panels parallel (4p), 3panels parallel*1panel series (3p*1s), 2panels parallel*2panels parallel (2p*2p) connected in series, and 2panels series*2panels series (2s*2s) connected in parallel, to determine the best PV panels configuration for supplying DC power to the Variable Speed Compressor (VSC) with the highest average exergy efficiency and minimum exergy losses under sunny daylight hours. Experimental data is used to calculate the exergy efficiency of the mentioned configurations. The best results are delivered by (2p*2p) configuration with average exergy efficiency of 43.77% and exergy efficiency of 88.05%. Whereas the percentage of improvement for the average exergy efficiency of this configuration compared with the (2s*2s), (4p), and (3p*1s) are (55.93%), (63.69%) and (78.9%) respectively.

1. Introduction

Energy demand has been globally overgrown for more than decades, which is proportional to the economic and population extension. Thereby, it becomes crucial to develop a convenient energy source to meet that increasing demand. Energy is a critical asset for all developing countries, and the fuel prices have increased beyond control due to the rising demands and power utilization. In addition, the supply of fossil deposits is expected to be declined in the coming decades and more efficient resources should be considered. Solar energy is one of the most viable sources of electricity that is readily available and can be obtained in an infinite amount [1]. In most of the available research, a single solar panel was analyzed while neglecting to analyze a group of panels and changing the configuration to derive the convenient design for the best exergy losses, energy efficiency where the panels' connectivity changed within the exact times and conditions and during certain hours. Therefore, analysis of the photovoltaic (PV) system has been of interest in many kinds of literature such as S.D. Deshmukh et al. [2] studied the effect of exergy analysis and energy analysis on the PV with and without load. It was noted that the exergy efficiencies with and without load were (11.2%-11.4%), respectively. On the other hand, the energy efficiencies with and without load were (8.2%-8.4%), respectively. K. Sudhakar, et al. [3] studied the utilization of energy and exergy analyses of the PV panel, which was installed at Energy Centre, NIT Bhopal, India. The results showed that the PV panel delivered low exergy efficiency with a value of (8.5%), while the rates of energy and exergy efficiencies were found to be 6.4% and 8.5%, respectively. Ami Shukla, et al. [4] evaluated thermal, electrical, and exergy output of the PV panel (Tata BP 184459) at Energy Centre, MANIT Bhopal. It was observed that the energy and exergy efficiencies were varying between (6% to 9%) and (8% to 10%), respectively. Mehmet Özalp et al. [5] evaluated the energy efficiency of the PV panel for several years, with the result coming in 2009 is 9.25% to 18.32%, and the energy efficiency in 2003 as calculated by Patella ranged between 9.41% and 9.41%, 18.64%, the excessive efficiency presented by Sahin et al. From 6.58% to 19.99%. Erhan Arslan et al. [6] analyzed the effect of energy and exergy measurements of a naturally ventilated PV roof solar. The system's thermal, electrical, and overall energy efficiencies were 18-50 %, 13-18 %, and 35-67 %, respectively, overall exergy competencies of the-RSC system ranged from 0.1-0.9 %, 14-20 %, and 15-21 %.

2. Methodology

2.1 Energy Analysis

The energy efficiency of the PV panel can be calculated from the ratio of the energy output of the system to energy input received on the surface of photovoltaic as:

$$\eta_{en} = \frac{V_{oc} I_{sc}}{S} \quad (1)$$

V_{oc} =open circuit voltage(V).

η_{en} =Energy Efficiency (%).

I_{sc} =Short Circuit Current (A).

The energy efficiency is limited to hypothetical cases. In eq. 1, S is solar flux absorbed, and it is given

$$\text{by: } S = G \cdot A_{mod} \quad (2)$$

$$A_{mod} = L1 \cdot L2 \quad (3)$$

Where L1 and L2 are the length and width of the solar modules respectively.

A_{mod} =Area of Module (m^2).

L1, L2=Length and Width of Module (m).

G=Solar Insolation (W/m^2).

The maximum power point of fill factor (FF), which is given as:

$$FF = \frac{V_{mp} I_{mp}}{V_{oc} I_{sc}} \quad (4)$$

I_{mp} =Current at Maximum Power Point (A).

V_{mp} =Voltage at Maximum Power Point (V).

FF=Fill Factor.

2.2 Exergy Analysis

The exergy is a thermodynamic case function that enables the exemplarily maximum obtainable part of any form of energy to be calculated, with maintaining the first and the second laws of the thermodynamic [7,8].

$$\dot{E}_{in} - \dot{E}_{out} = \dot{E}_{dest} = \dot{E}_{loss} \quad (5)$$

PV panel exergy efficiency (%) is the ratio of total exergy output to exergy output [7,8]. The exergy ratio obtained by PV to solar radiation exergy is also known as PV exergy efficiency [9].

$\dot{E}_{Xdes}$ =Exergy Destruction Rate (W).

$\dot{E}_{in}$ =Inlet Exergy Rate (W).

$\dot{E}_{Xloss}$ =Exergy Loss (W).

$\dot{E}_{Xout}$ =Outlet Exergy Rate (W).

$$\eta_{ex} = \frac{\dot{E}_{out}}{\dot{E}_{in}} \quad (6)$$

η_{ex} =Exergy Efficiency (%).

The PV system's inlet exergy only contains the solar radiation intensity exergy. As for the theorem of the patella, as: [9,10].

$$\dot{E}_{in} = G A_{mod} \left[1 - \frac{4}{3} \left(\frac{T_{amb}}{T_{sun}} \right) + \frac{1}{3} \left(\frac{T_{amb}}{T_{sun}} \right)^4 \right] \quad (7)$$

T_{amb} = Ambient Temperature ($^{\circ}K$).

T_{sun} = 5780 Sun temperature ($^{\circ}K$).

Outlet exergy of PV system determined by [11]

$$\dot{E}_{x(pv) out} = \dot{E}_{xout} = V_m I_m - \left(\frac{T_{mod}}{T_{amb}} \right) [h c A_{mod} (T_{mod} - T_{amb})] \quad (8)$$

V_m =maximum voltage (v).

I_m =maximum current (A).

T_{amb} = Ambient Temperature ($^{\circ}K$).

T_{mod} = Module Temperature ($^{\circ}K$).

Exergy of the thermal energy.

$$\dot{E}_{th} = Q \left[1 - \left(\frac{T_{amb}}{T_{mod}} \right) \right] \quad (9)$$

$\dot{E}_{th}$ =Thermal Exergy Rate (W).

Q =heat emitted to the surrounding (W).

$$Q = U A_{mod} (T_{mod} - T_{amb}) \quad (10)$$

The overall coefficient of the heat loss PV panel includes losses of conversion and radiation.

$$U = (h_{conv} + h_{rad}) \quad (11)$$

h_{conv} =Convection Heat Transfer Coefficient (W/m² k)

h_{rad} =Radiation Heat Transfer Coefficient (W/m²)

Coefficient of Convective Heat Transfer [12]

$$h_{conv} = 2.8 + 3V_w \quad (12)$$

V_w =wind speed (m/s).

Irradiative coefficient of heat transfer between the PV panel and the surrounding environment [13]

$$h_{rad} = \epsilon \sigma (T_{sky} - T_{mod})(T_{sky}^2 + T_{mod}^2) \quad (13)$$

σ =Stefan Boltzmann constant 5.67×10⁻⁸ w/m²K

ϵ =Emissivity of the panel

T_{sky} =Sky Temperature (°K)

Effective temperature of the sky [18]

$$T_{sky} = T_{amb} - 6 \quad (14)$$

Exergy electrical in output power electrical of PV panel [13]

$$\dot{E}_{el} = V_{oc} I_{sc} FF \quad (15)$$

$\dot{E}_{el}$ Electrical Exergy Rate (W).

The average exergy efficiency improved

$$\eta = \left(\frac{\eta(2P*2P) - \eta(4P) \text{ or } (2S*2S) \text{ or } (3S+1P)}{\eta(2P*2P)} \right) 100\% \quad (16)$$

η The average exergy efficiency improved (%)

$\eta(2P*2P)$ The average exergy efficiency (2Panels Parallel *2Panels Parallel)connected in series %

$\eta(2S*2S)$ The average exergy efficiency (2Panels series*2Panels series)connected in parrallel %

$\eta(4P)$ The average exergy efficiency (4Panels parallel)

$\eta(3P+1S)$ The average exergy efficiency (3 Panels parallel +1panel in series)%

3. Experimental set up

The overall experimental setup of the PV system is shown in Figure 1. The system consists of a Mono-Crystalline Solar Panel PV panel with 50 W. Table 1 lists the manufacturer specifications of the PV. In Figure 2 the devices used in the experimental. It measures the 1-5 characteristic curve of the PV systems Solar Energy Research Center, The included test results below are specified for four panels, The panels were mounted with 49.1 degrees tilt angle to the south in Baghdad city shown in Figure 3. A sample calculation for a typical set of design parameters in December is given in Table 2, this Table gives an insight into the variation of the characteristics, energy efficiency, current, the voltage in the different configuration arrays. In addition, all measurement instruments used in this study and their related applications are listed in Table 3.



Figure 1: Experimental setup

Table 1: PV panels properties

Parameter	Specification
Model	Mono Crystalline Solar Panel
Maximum power (W)	50W
Maximum power t voltage/Vmp(V)	18V
Maximum power current/Imp(A)	2.77A
Short Circuit Current/Isc(A)	2.99A
Short Circuit Voltage/Vsc(V)	21.6V
Maximum power Tolerance	$\pm 5\%$
Product Size	680*510*30 mm



Solar Power meter



Digital Multimeter



Multimeter with Temperatur Wind Speed meter

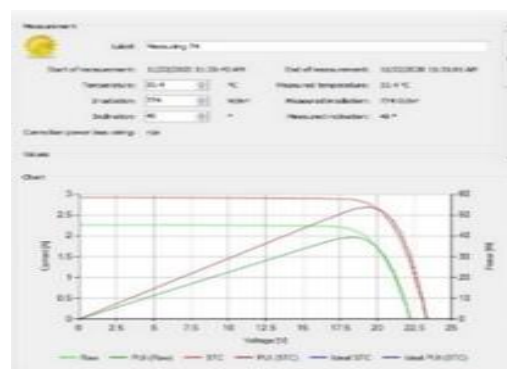
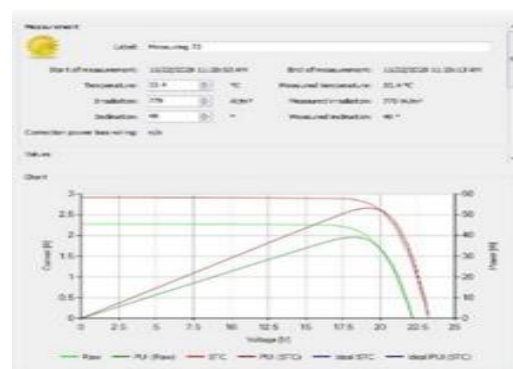
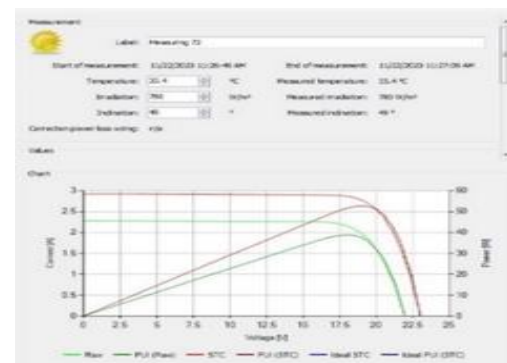
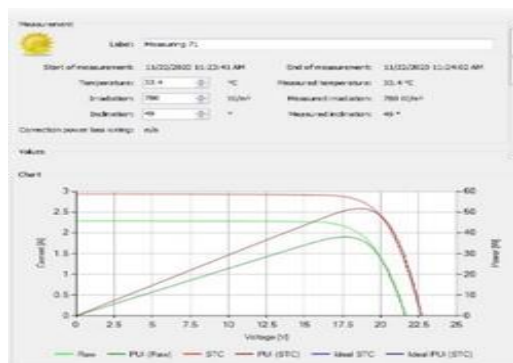
**Figure 2:** Utilized Measurement Equipment**Figure 3:** energy center research (Baghdad)

Table 2: The following parameters were measured by various instruments used for testing

Time	4 Panels parallels			3 Panels parallel + 1 series			2 x 2 Panels parallel connected in series			2 x 2 Panels series connected in Parallel			radation w/m ²
	I A	V volt	energy %	I A	V volt	energy %	I A	V volt	energy %	I A	V volt	energy %	
8:00AM	3.28	21.7	26.38%	2.1	42.9	34.57%	1.4	43.8	23.93%	1.4	43.3	23.93%	195
8:30AM	4.25	21.7	31.73%	2.3	42.8	34.81%	2.7	43.2	40.56%	2.6	43.4	40.56%	210
9:00AM	6.89	21.4	29.60%	2.9	42.1	24.59%	3.4	43.1	28.10%	3.2	42.7	28.10%	360
9:30AM	7.76	21.2	23.31%	3.4	41.9	20.24%	3.7	42.5	22.57%	3.7	42.3	22.57%	510
10:00AM	9.05	21.2	18.99%	3.7	41.6	15.24%	4.6	41.8	19.26%	4.6	42.3	19.26%	730
10:30AM	9.28	21	17.83%	3.7	41.6	14.24%	4.7	41.8	18.01%	4.7	41.8	18.01%	790
11:00AM	10.5	21	17.74%	3.9	41.6	13.10%	5.2	41.2	17.17%	5.1	41.9	17.17%	900
11:30AM	10.5	20.9	16.81%	4.0	41.3	12.63%	5.3	41.7	16.45%	5.2	41.5	16.45%	950
12:00PM	10.2	20.9	19.19%	3.9	41.7	14.59%	5.1	41.5	18.88%	5.2	41.2	18.88%	810
12:30PM	9.82	20.9	20.04%	2.9	41.4	11.80%	4.5	41.2	18.87%	4.6	41.9	18.87%	740
1:00PM	8.92	20.9	19.38%	2.2	41.9	9.95%	4.4	41.8	20.16%	4.6	41.1	20.16%	695
1:30PM	8.2	20.9	20.30%	2.0	41.8	10.35%	4.2	41.6	20.85%	4.1	41.4	20.85%	610
2:00PM	7.1	20.9	19.32%	1.7	41.7	9.63%	3.6	41.5	18.41%	3.7	43.2	18.41%	555
2:30PM	6.44	20.8	18.62%	1.5	41.7	9.10%	3.2	41.4	19.90%	3.3	43.9	19.90%	520
3:00PM	5.85	20.8	18.87%	1.5	41.7	9.70%	3.1	41.4	30.14%	3.0	42.4	30.14%	466
3:30PM	4.26	20.8	28.33%	0.8	41.5	6.27%	2.0	41.9	30.14%	2.2	41.5	30.14%	226
4:00PM	3.88	20.6	30.72%	0.5	41.6	8.83%	1.9	41.3	24.26%	1.3	41.8	24.26%	188

Table 3: Specification of all measuring instruments

Serial No.	Name of measuring	Manufacturing and Model No.	Rataing	Application
1	Solar power meter	SM206_solar	0.1_1999.9w/m2	Solar radiation intensity
2	DIGITAL Multimeter	DT9205A	2m_20A,2V_1000V	PV module characteristics
3	DIGITAL Multimeter	DT 33C	(-40 °C +1000 °C)	Ambient tempresure &Temperature cell
4	Thermocouple	Type K	-270 to 1260 °C	Temperature cell
5	Wind speed meter	GM8910	0_30 m/s	Wind speed

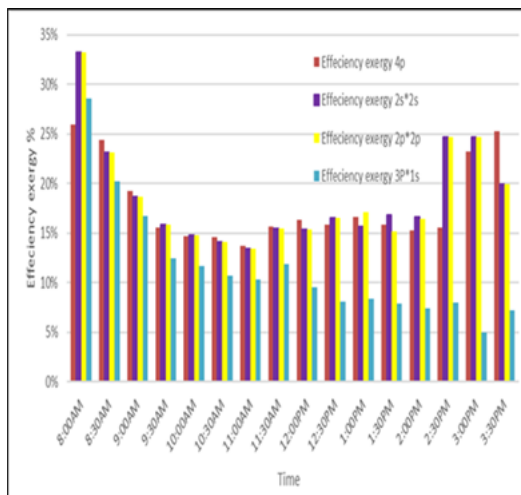


Figure 4: Variation of efficiency exergies for clear days

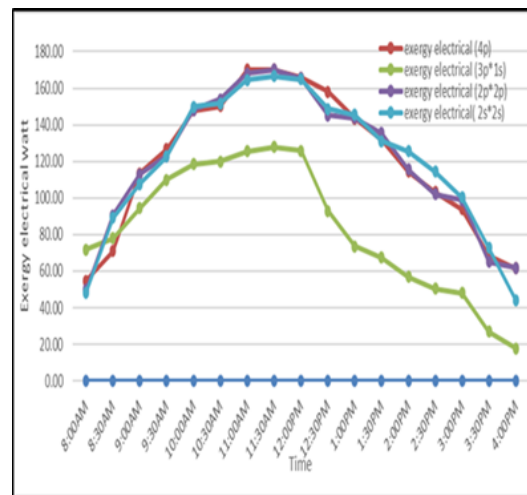


Figure 5: The variation exergy electrical with the time of PV module

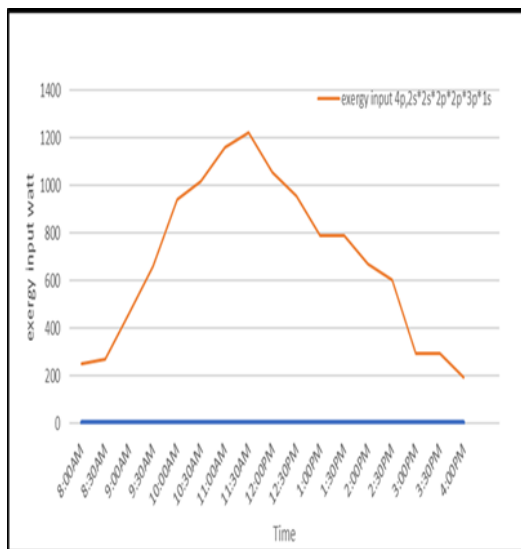


Figure 6: The variation input exergy with the time of PV module

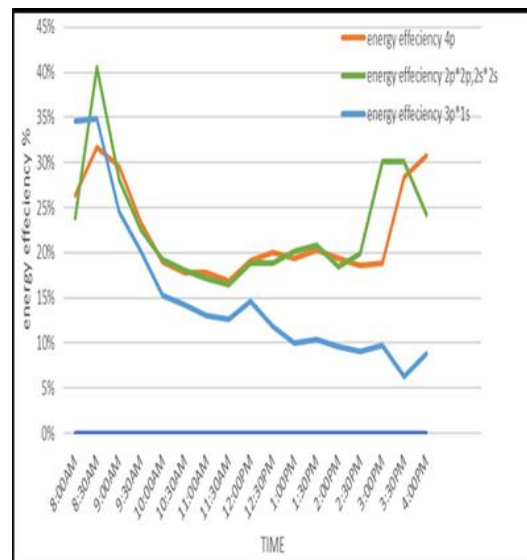


Figure 7: The variation energy efficiency with the time of PV module

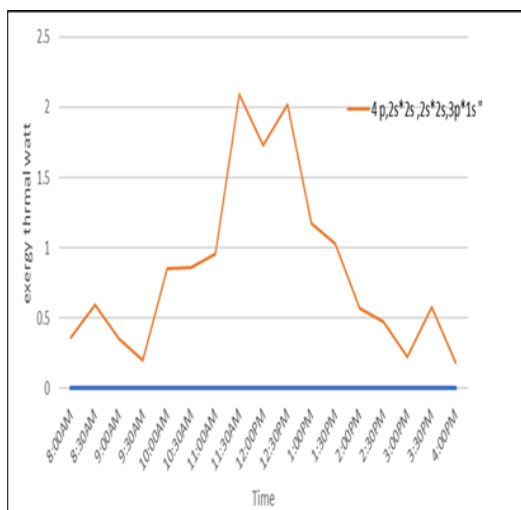


Figure 8: The variation exergy thermal with the time of PV module

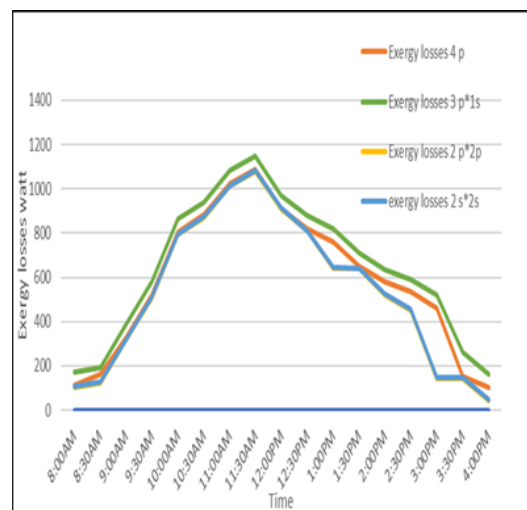


Figure 9: The variation exergy losses with the time of PV module

4. Results and discussion

The mentioned PV configurations have been analyzed and compared. The experiments have been carried out on the same condition, i.e., all the obtained data were measured on December 2020 from 8:00 am to 4:00 pm with 30-minute intervals. Figure 4 compared the exergy efficiencies of the four PV configurations. The maximum efficiency exergy is 33%, delivered by 2s*2s, 2p*2p at the same time, the efficiency exergies of 4p and 3p*1s are 26%, 29%, respectively. The exergy efficiency was on its highest levels at 8:00 am as a result of the low (exergy in) values because of the low solar radiation intensity and ambient temperature, that would affect is inversely proportional to the exergy efficiency, As well as increasing maximum exergy work ($V_m * I_m$), that is directly proportional to Exergy out thus increasing efficiency exergy. The experimental results indicated that the exergy efficiency is at the maximum values with (2S * 2s) PV configuration, which is an expected result because of the low current extracted from this PV configuration. In addition to that, the slack losses have reached low values and thus increase the exergy out, which is directly proportional to the exergy efficiency, and thus it performs an increase in the exergy efficiency of the of (2s * 2s) PV configuration. Figure 5 demonstrates the behavior of the electrical efficiency of the four PV configurations during the day. The minimum value is 17.67 watts for the 3p*1s configuration, while the 2P*2p configuration has the maximum electrical efficiency with the value of 170.17watts. Readings of all solar panel configurations. The results of all PV configurations arrays show that the electrical exergy at their highest levels from 11 am to 1 pm; despite the decrease in voltage, the electrical exergy has not been affected due to the increase in the current. The experimental results of the electrical exergy were higher for the (4p) PV configuration due to the rise in the current while maintaining a constant voltage.

Figure 6 shows the results of the input exergy during the day. The maximum input exergy was 1224.20 watt, while the minimum input exergy was 194.95 watt in all the configurations. It is noted from this figure that the PV array configuration has no influence on the exergy input, considering that current and voltage were not parameters in Eq. (7).

Figure 7 shows the exergy efficiency during the day for all configurations. The maximum energy efficiency is 40.56% for the 2s*2s at 8:30 am, while the minimum energy efficiency is 6.27% obtained by the 3p*1s configuration at 3:30 pm. It can be concluded that a considerable amount of usable exergy is wasted, and the silicon panel only makes a minor contribution to the strong exergy of sunlight. Silicon solar cells have poor exergy efficiency due to their low energy performance. Additionally, it was noticed that the relationship between solar radiation and energy efficiency is inversely proportional based on Eq. (1).

Figure 8 shows exergy thermal during the day for the understudying configurations. The maximum and minimum recorded exergy thermal was 2.0198 watt and 0.1843 watts, respectively, in 2s*2s configuration. It is observed from this figure that the thermal exergy is not affected by PV array configuration as these different configurations were tested under the same conditions. Considering that current and voltage are not parameters in equation (9).

Figure 9 shows the exergy losses during the day for the understudying configurations. The percentage losses of exergy were reached about 89.04% throughout the day for the (3 P *1s) PV array configuration; this is because of the significant difference between exergy out and exergy, leading to an increase in Exergy Losses.

5. Conclusions

Experimental exergetic and energetic analysis for PV panels with four array configurations have been carried out, to check the exergy efficiency and conservation of the energy under local climate and the same operating conditions. Based on the obtained experimental result, the following calculations are drawn:

- 1) The maximum and minimum exergy efficiency for 4 Panels in parallels are 54.75 % and 10.96%, 3 p*1s 32.98% and 6.21%, 2s*2s are 75.03% and 11.62%, 2p*2p are 88.05% and 22.88%, respectively.
- 2) Array configuration has no influence on both exergy input and exergy thermal.
- 3) The minimum exergy losses and maximum exergy electrical for 4 p, 3 p*1s, 2s*2s, 2p*2p were 44.60-watt, 1090 watt respectively.
- 4) The maximum efficiency energy was 8.83% in the 3p*1s configuration, and the minimum efficiency energy was 40.65% of the two cases, which are 2p*2p and 2s*2s.
- 5) The percentage of improvement for the average exergy efficiency of the case (2p*2p) compared with the cases (2s*2s), (4p) and (3p*1s) were (55.93%), (63.69%) and (78.9%) respectively.
- 6) The results of analyzing the PV array configuration can be applied in a Variable Speed Compressor by selecting the most convenient setup.

Author contribution

All authors contributed equally to this work.

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Data availability statement

The data that support the findings of this study are available on request from the corresponding author.

Conflicts of interest

The authors declare that there is no conflict of interest.

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